

Implication of Higgs mediated Flavour Changing Neutral Currents with Minimal Flavour Violation

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Abstract. We analyse phenomenological implications of two Higgs doublet models with Higgs flavour changing neutral currents suppressed in the quark sector by small entries of the Cabibbo-Kobayashi-Maskawa matrix. This suppression occurs in a natural way since it is the result of a symmetry applied to the Lagrangian. These type of models were proposed some time ago by Branco Grimus and Lavoura. Our results clearly show that these class of models allow for new physical scalars, with masses which are reachable at the LHC. The imposed symmetry severely reduces the number of free parameters and allows for predictions. Therefore these models can eventually be proved right or eliminated experimentally.

1. Introduction

There are several good motivations to consider models with two Higgs doublets. Such models allow for new sources of CP violation and for the possibility of having spontaneous CP violation. It is by now established that the SM cannot account for the observed baryon asymmetry of the universe and that new sources of CP violation are required. Spontaneous CP violation was first proposed by Lee [1] in the context of two Higgs doublet models (2HDM) and puts CP violation on the same footing as the electroweak symmetry breaking. Models with two Higgs doublets may also provide a solution to the strong CP problem of the type proposed by Peccei and Quinn [2]. Furthermore, supersymmetric extensions of the Standard Model (SM) also require the existence of two Higgs doublets.

The discovery of a scalar boson in the run 1 of LHC by Atlas [3] and CMS [4] immediately raises the question of whether this is the SM Higgs boson or part of a multi-Higgs theory. The properties of the Higgs boson already discovered are up till now in good agreement with those predicted by the SM but more precise determinations may show evidence for New Physics. There is also the possibility that the LHC will soon discover a charged Higgs or additional neutral scalars thus confirming the need to extend the scalar sector of the SM.

There are important experimental constraints on 2HDM. Such models have potentially large Higgs mediated flavour changing neutral currents (FCNC) [5], [6] [7]. Effects due to these FCNC are severely constrained and therefore some mechanism to suppress these effects is required. It is possible to eliminate tree level FCNC by imposing for instance natural flavour conservation [8] or alignment [9]. Another possibility, which was proposed some time ago by Branco Grimus

and Lavoura (BGL) [10], consists on imposing a symmetry on the Lagrangian allowing for tree level FCNC in the quark sector suppressed by small entries of the Cabibbo–Kobayashi–Maskawa matrix, V_{CKM} . Later-on, BGL models were extended to the leptonic sector [11] and their relation to Minimal Flavour Violation models has been studied [12]. Phenomenological implications of these models have been analysed recently [13], [14], [15]. This talk is largely based on work done in Ref. [14].

2. Theoretical Framework

In Ref. [14] we analysed extensions of the SM with two Higgs doublets together with three right-handed neutrinos. We did not add Majorana mass terms to the Lagrangian and as a result neutrinos are Dirac type. However our analysis of phenomenological implications is not sensitive to the character of the neutrinos. The Yukawa interactions can be explicitly written:

$$\begin{aligned}\mathcal{L}_Y = & -\overline{Q_L^0} \Gamma_1 \Phi_1 d_R^0 - \overline{Q_L^0} \Gamma_2 \Phi_2 d_R^0 - \overline{Q_L^0} \Delta_1 \tilde{\Phi}_1 u_R^0 - \overline{Q_L^0} \Delta_2 \tilde{\Phi}_2 u_R^0 \\ & - \overline{L_L^0} \Pi_1 \Phi_1 \ell_R^0 - \overline{L_L^0} \Pi_2 \Phi_2 \ell_R^0 - \overline{L_L^0} \Sigma_1 \tilde{\Phi}_1 \nu_R^0 - \overline{L_L^0} \Sigma_2 \tilde{\Phi}_2 \nu_R^0 + \text{h.c.},\end{aligned}\quad (1)$$

where Γ_i , Δ_i , Π_i and Σ_i denote the Yukawa couplings to the right-handed quarks d_R^0 , u_R^0 , right-handed leptons ℓ_R^0 , ν_R^0 , respectively, and the Higgs doublets Φ_j . The quark mass matrices generated after spontaneous gauge symmetry breaking are given by:

$$M_d = \frac{1}{\sqrt{2}}(v_1 \Gamma_1 + v_2 e^{i\alpha} \Gamma_2), \quad M_u = \frac{1}{\sqrt{2}}(v_1 \Delta_1 + v_2 e^{-i\alpha} \Delta_2), \quad (2)$$

where $v_i \equiv |\langle 0 | \phi_i^0 | 0 \rangle|$ and α denotes the relative phase of the vacuum expectation values (vevs) of the neutral components of Φ_i . The matrices M_d , M_u are diagonalized by the usual bi-unitary transformations:

$$U_{dL}^\dagger M_d U_{dR} = D_d \equiv \text{diag} (m_d, m_s, m_b) \quad (3)$$

$$U_{uL}^\dagger M_u U_{uR} = D_u \equiv \text{diag} (m_u, m_c, m_t) \quad (4)$$

The neutral and the charged Higgs interactions obtained from Eq. (1) for the quark sector are of the form

$$\begin{aligned}\mathcal{L}_Y(\text{quark, Higgs}) = & -\overline{d_L^0} \frac{1}{v} [M_d H^0 + N_d^0 R + i N_d^0 I] d_R^0 - \\ & - \overline{u_L^0} \frac{1}{v} [M_u H^0 + N_u^0 R + i N_u^0 I] u_R^0 - \\ & - \frac{\sqrt{2} H^+}{v} (\overline{u_L^0} N_d^0 d_R^0 - \overline{u_R^0} N_u^{0\dagger} d_L^0) + \text{h.c.}\end{aligned}\quad (5)$$

where $v \equiv \sqrt{v_1^2 + v_2^2} \approx 246$ GeV, and H^0 , R are orthogonal combinations of the fields ρ_j , arising when one expands [1] the neutral scalar fields around their vacuum expectation values, $\phi_j^0 = \frac{e^{i\alpha_j}}{\sqrt{2}}(v_j + \rho_j + i\eta_j)$, choosing H^0 in such a way that it has couplings to the quarks which are proportional to the mass matrices, as can be seen from Eq. (5). Similarly, I denotes the linear combination of η_j orthogonal to the neutral Goldstone boson. The matrices N_d^0 , N_u^0 are given by:

$$N_d^0 = \frac{1}{\sqrt{2}}(v_2 \Gamma_1 - v_1 e^{i\alpha} \Gamma_2), \quad N_u^0 = \frac{1}{\sqrt{2}}(v_2 \Delta_1 - v_1 e^{-i\alpha} \Delta_2) \quad (6)$$

It is clear from these expressions that the flavour structure of the quark sector of two Higgs doublet models is much richer than that of the SM requiring the four matrices M_d , M_u , N_d^0 , N_u^0 in order to be fully specified. For the leptonic sector one can derive similar expressions and the corresponding matrices can be denoted by M_ℓ , M_ν , N_ℓ^0 , N_ν^0 . In the leptonic sector with Dirac neutrinos the analogy with the quark sector is perfect.

Flavour changing neutral currents in the quark sector are controlled by N_d^0 and N_u^0 while in the leptonic sector they are controlled by N_ℓ^0 , N_ν^0 .

In terms of physical quarks the neutral and the charged Higgs interactions can be written:

$$\begin{aligned} \mathcal{L}_Y(\text{quark, Higgs}) = & -\frac{\sqrt{2}H^+}{v}\bar{u}\left(VN_d\gamma_R - N_u^\dagger V\gamma_L\right)d + \text{h.c.} - \\ & -\frac{H^0}{v}\left(\bar{u}D_u u + \bar{d}D_d d\right) - \frac{R}{v}\left[\bar{u}(N_u\gamma_R + N_u^\dagger\gamma_L)u + \bar{d}(N_d\gamma_R + N_d^\dagger\gamma_L)d\right] + \\ & + i\frac{I}{v}\left[\bar{u}(N_u\gamma_R - N_u^\dagger\gamma_L)u - \bar{d}(N_d\gamma_R - N_d^\dagger\gamma_L)d\right] \end{aligned} \quad (7)$$

where γ_L and γ_R are the left-handed and right-handed chirality projectors, respectively, and $N_d \equiv U_{dL}^\dagger N_d^0 U_{dR}$, $N_u \equiv U_{uL}^\dagger N_u^0 U_{uR}$, $V \equiv U_{uL}^\dagger U_{dL}$. The matrix V is a simplified notation for the V_{CKM} matrix. There are analogous expressions for the leptonic sector with V_{CKM} replaced by the Pontcorvo-Maki-Nakagawa-Sakata matrix, U_{PMNS} . The physical neutral Higgs fields are combinations of H^0 , R and I .

Up till this point the discussion applies to the general two Higgs doublet model with Dirac fermions. The matrices N_d , N_u , N_ℓ and N_ν are entirely arbitrary and the scalar potential is the most general one for two Higgs doublets.

In order to suppress the tree level FCNC in the quark sector by means of small entries of V_{CKM} Branco, Grimus and Lavoura imposed the following symmetry on the quark and scalar sector of the Lagrangian [10]:

$$Q_{Lj}^0 \rightarrow \exp(i\tau) Q_{Lj}^0, \quad u_{Rj}^0 \rightarrow \exp(i2\tau) u_{Rj}^0, \quad \Phi_2 \rightarrow \exp(i\tau)\Phi_2, \quad (8)$$

where $\tau \neq 0, \pi$, with all other quark fields transforming trivially under the symmetry. The index j can be fixed as either 1, 2 or 3. Alternatively the symmetry may be chosen as:

$$Q_{Lj}^0 \rightarrow \exp(i\tau) Q_{Lj}^0, \quad d_{Rj}^0 \rightarrow \exp(i2\tau) d_{Rj}^0, \quad \Phi_2 \rightarrow \exp(-i\tau)\Phi_2. \quad (9)$$

The symmetry given by Eq. (8) leads to Higgs FCNC in the down sector only, whereas the symmetry specified by Eq. (9) leads to Higgs FCNC only in the up sector. These two alternative choices of symmetry combined with the three possible ways of fixing the index j give rise to six different realisations of 2HDM with the flavour structure, in the quark sector, controlled by the V_{CKM} matrix. The models obtained from the symmetry defined by Eq. (8) are called up-type models. In these models N_d and N_u have the simple form:

$$(N_d)_{rs} = \frac{v_2}{v_1}(D_d)_{rs} - \left(\frac{v_2}{v_1} + \frac{v_1}{v_2}\right)(V_{CKM}^\dagger)_{rj}(V_{CKM})_{js}(D_d)_{ss} \quad (10)$$

no sum in j implied, whereas, particularising the index j to be 3, we have:

$$N_u = -\frac{v_1}{v_2}\text{diag}(0, 0, m_t) + \frac{v_2}{v_1}\text{diag}(m_u, m_c, 0) \quad (11)$$

the index j fixes the row of V_{CKM} which suppresses the flavour changing neutral currents. For down-type models, which are those obtained from imposing the symmetry defined by Eq. (9),

the two matrices N_d and N_u exchange rôle and the FCNC are now suppressed by one of the columns of V_{CKM} depending on the index j .

As a result of imposing such a symmetry the matrices N_d and N_u are entirely determined by fermion masses, the V_{CKM} matrix and the angle β defined by $\tan \beta = v_2/v_1$, with no other free parameters. The flavour structure of BGL models depends on parameters already present in the SM apart from the new parameter $\tan \beta$. This characteristic is a defining feature of models that have been later-on denoted as models of Minimal Flavour Violation type [16], [17], [18], [19].

The leptonic sector with Dirac neutrinos is analogous to the quark sector and again there are six possible different realisations. Combining the two sectors one obtains thirty six different models which can be identified by a set of two indices. For example, the model $(\text{up}_3, \ell_2) \equiv (t, \mu)$ will have no tree level neutral flavour changing couplings in the up quark and the charged lepton sectors while the neutral flavour changing couplings in the down quark and neutrino sectors will be controlled, respectively, by V_{td_i} , $V_{td_j}^*$ and $U_{\mu\nu_a}$, $U_{\mu\nu_b}^*$.

The scalar potential is also constrained by the imposed symmetry. With the introduction of a soft symmetry breaking term it will have seven independent parameters which will determine the four scalar masses, the combination $v \equiv \sqrt{v_1^2 + v_2^2}$, $\tan \beta \equiv v_2/v_1$, and α . The angle α is the mixing angle relating the physical neutral CP-even scalars to the fields ρ_1 and ρ_2 . One mixing angle is sufficient since this constrained scalar potential does not violate CP neither explicitly nor spontaneously [10] and therefore the field I is already physical. The soft symmetry breaking term prevents the appearance of an would-be Goldstone boson due to an accidental continuous global symmetry of the potential.

In the present work we assumed that H^0 coincides with the observed Higgs boson. Deviations from this assumption are still allowed by the experimental data but are constrained to be small. This assumption corresponds to imposing $\beta - \alpha = \pi/2$. The masses of the extra Higgs bosons must obey constraints coming from electroweak precision tests, in particular the T and S parameters. Bounds on T and S together with direct mass limits, significantly constrain the masses of the new scalar fields in terms of the mass of the charged Higgs H^\pm [20] so that once this mass is fixed there is not much freedom left for the masses of the extra neutral scalars. As a result we can approximately scan the whole region of parameter space by varying $\tan \beta$ and the mass, m_{H^\pm} , of the charged Higgs boson.

3. Confrontation with the experimental results

We performed an analysis of the thirty six BGL models in order to determine where could the masses of the new scalars lie and how these depend on $\tan \beta$. The masses of all new three scalar fields were treated independently and on an equal footing even though for simplicity we only presented results in terms of m_{H^\pm} . As stated in the previous section we assumed that the discovered Higgs at the LHC coincides with our H^0 scalar, the one without FCNC.

We imposed present constraints from several relevant flavour observables. In Table 1 we summarise the different types of relevant observables that we took into consideration, indicating where the contributions come from. In some cases the new contributions are only present in some but not all of the models. In Ref. [14] we give a detailed description of the analysis that we performed and we list the set of experimental data and bounds that we used.

Figures 1 and 2 present the allowed regions we obtained for each one of the thirty six models.

Some of the BGL models allow for masses of the charged Higgs below 380 GeV which is the constraint from $b \rightarrow s\gamma$ on type II 2HDMs [21]. This is due to the different dependence that these models have on $\tan \beta$. However, in general, loop level processes, such as $b \rightarrow s\gamma$ as well as $\ell_j \rightarrow \ell_i\gamma$ provide important constraints. The same is true for the process $Z \rightarrow b\bar{b}$ and the oblique parameters S and T , unlike U .

	BGL - 2HDM				SM	
	Charged H^\pm		Neutral R, I		Tree	Loop
	Tree	Loop	Tree	Loop		
$M \rightarrow \ell \bar{\nu}, M' \ell \bar{\nu}$	X	x		x	X	x
Universality	X	x		x	X	x
$M^0 \rightarrow \ell_1^+ \ell_2^-$		x	X	x		X
$M^0 \leftrightarrow M^0$		x	X	x		X
$\ell_1^- \rightarrow \ell_2^- \ell_3^+ \ell_4^-$		x	X	x		x
$B \rightarrow X_s \gamma$		X		X		X
$\ell_j \rightarrow \ell_i \gamma$		X		X		x
EW Precision		X		X		X

Table 1. Summary table of the different types of relevant observables; leading contributions are tagged X while subleading or negligible ones are tagged x .

Concerning electric dipole moments of leptons and quarks [22], [23] BGL models do not give new physics one loop contributions. In [24] it has been shown that the weak basis invariant relevant for the quark EDMs does not acquire an imaginary part. In fact the same applies to two loop contributions within BGL models..

4. Conclusions

BGL models are very constrained since they have a very small number of free parameters and therefore they are highly predictive allowing to establish correlations among different observables. This also means that in principle it will be possible to rule out several of these different scenarios based on the future LHC results. Our results show that there are some very promising BGL implementations, which deserve more attention.

Several of the models allow for scalar masses within the reach of direct searches at the LHC.

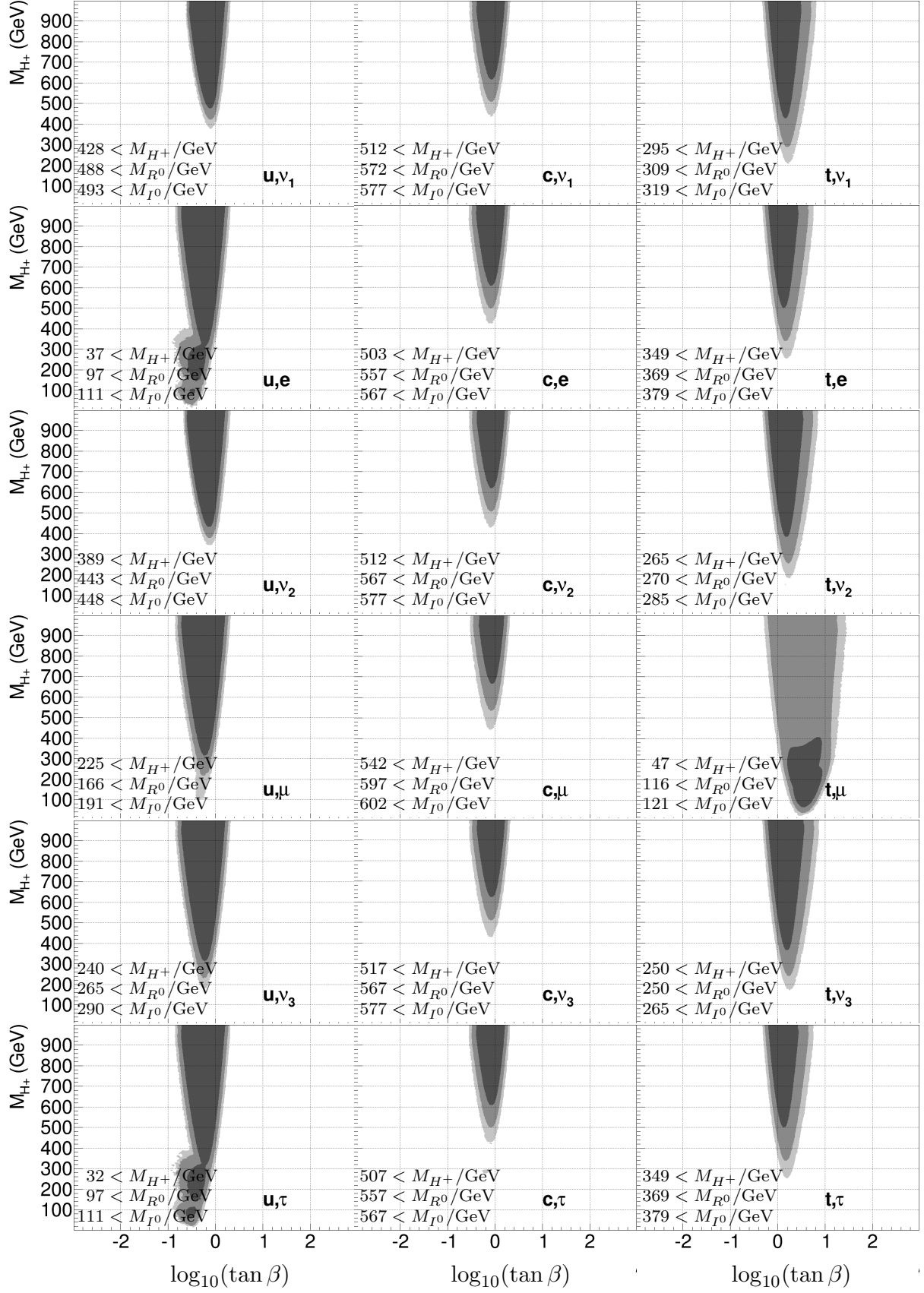


Figure 1. Allowed 68% (black), 95% (gray) and 99% (light gray) CL regions in m_{H^\pm} vs. $\tan \beta$ for BGL models of types (u_i, ν_j) and (u_i, ℓ_j) , i.e. for models with FCNC in the down quark sector and in the charged lepton or neutrino sector (respectively). Lower mass values corresponding to 95% CL regions are shown in each case.

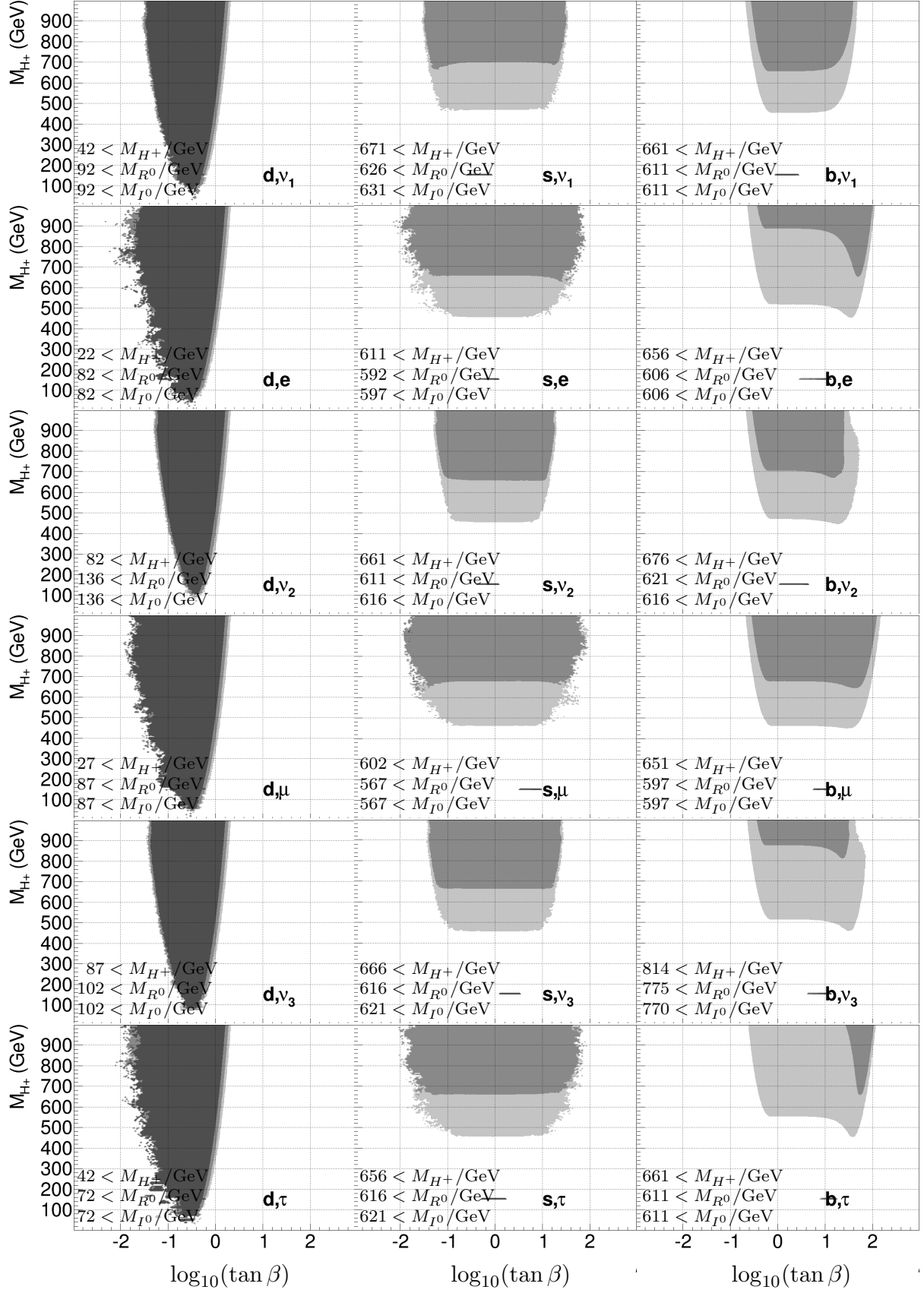


Figure 2. Allowed 68% (black), 95% (gray) and 99% (light gray) CL regions in m_{H^\pm} vs. $\tan \beta$ for BGL models of types (d_i, ν_j) and (u_i, ℓ_j) , i.e. for models with FCNC in the up quark sector and in the charged lepton or neutrino sector (respectively). Lower mass values corresponding to 95% CL regions are shown in each case.

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